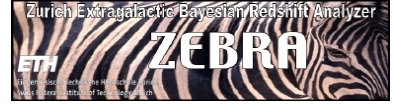




Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



The Zurich Extragalactic Bayesian Redshift Analyzer (ZEBRA)

Version 1.0 – User manual

<http://www.exp-astro.phys.ethz.ch/ZEBRA>

February 1st, 2008

ZEBRA, the **Z**urich **E**xtragalactic **B**ayesian **R**edshift **A**nalyzer, is a tool for estimating redshifts and template types of galaxies using medium- and broad-band photometric data. ZEBRA employs novel techniques within the template-fitting approach to produce high-quality Maximum-Likelihood and Bayesian redshift estimates.

This manuscript serves as a user guide to ZEBRA v1.0. It explains how to use ZEBRA v1.0, specifies input and output formats, and gives a short account of the available options. The principles behind ZEBRA v1.0 are explained in the reference publication Feldmann et al. (2006).

ZEBRA v1.0 is a free and open-source software distributed under the GNU Public License 3. It is kindly requested that the use of ZEBRA should be acknowledged with an explicit reference to Feldmann et al. (2006) in the bibliographic list of any resulting publication.

Several upgrades are currently being implemented in ZEBRA. An updated documentation will be provided at each new release. Any problems, comments and suggestions on the code and the manual should be sent via e-mail to zebra@phys.ethz.ch.

Contents

1	Introduction	4
1.1	About ZEBRA	4
1.2	The software license	5
1.3	Usage and questions	5
2	Getting started	6
2.1	About this package	6
2.2	Installing ZEBRA	6
2.3	Checking the installation	7
2.4	How to use ZEBRA	7
3	Basic files and settings	10
3.1	Directories	10
3.2	The filter files	10
3.3	The template files	11
3.4	The catalog file	11
3.5	The standard configuration files	12
3.6	Other configuration files	14
3.7	Basic output files	14
3.8	Basic options	16
4	The different run modi of ZEBRA	17
4.1	Running the photometry-check mode	18
4.2	Running the template-optimization mode	22
4.3	Running the Maximum-Likelihood mode	24
4.4	Running the Bayesian mode	25
4.5	Running the k-correction mode	26
5	Background Information	26
5.1	Extensions of templates and the mesh	26
5.2	The use of cosmological parameters	27
5.3	The intergalactic absorption	27
5.4	Flux densities and normalization	27
6	Experimental features	29
A	GNU GENERAL PUBLIC LICENSE	30

1 Introduction

1.1 About ZEBRA

ZEBRA estimates redshifts and template types of galaxies using a photometric catalog. It is based on:

- (1.) An automatic iterative technique to correct the original set of galaxy templates to best represent the SEDs of real galaxies at different redshifts;
- (2.) A training set of spectroscopic redshifts for a small fraction of the photometric sample to improve the robustness of the photometric redshift estimates; and
- (3.) An iterative technique for Bayesian redshift estimates, which extracts the full two-dimensional redshift and template likelihood function for each galaxy.

Input The user can choose from, or has otherwise to provide, an initial set of templates and filter transmission curves, see Table 1 and Table 2. In addition, ZEBRA needs a catalog containing the magnitudes of the individual galaxies in the various filter bands (at least 3 filter bands are needed to run ZEBRA in *Maximum-Likelihood mode* or *photometry-check mode*). The different input files are described in detail in section 3.

Output ZEBRA offers a variety of output information depending on its run mode.

ZEBRA prints on-screen information during its execution. The level of verbosity of this output can be adjusted with the `-v/--verbosity` option.

When run in *photometry-check mode* ZEBRA returns a catalog with calibrated photometry together with detailed information about the applied changes.

In *template-optimization mode* ZEBRA returns the corrected templates as wavelength – flux density (per unit wavelength) tables.

If ZEBRA is run in *Maximum-Likelihood mode*, it will return the best fit redshift and template type together with their confidence limits estimated from constant χ^2 boundaries. Additionally, ZEBRA returns: (i) the minimum χ^2 , (ii) the normalization factor of the best fit template, (iii) the rest-frame B-band magnitude and (iv) the luminosity distance for the given cosmological Friedmann-Robertson-Walker model. If specified by the user, ZEBRA provides further information, e.g. the likelihood functions for all galaxies in several output formats or the residuals between best fit template magnitude and measured magnitude for each galaxy in each filter band.

In the *Bayesian mode* ZEBRA calculates the 2D-prior in redshift and template space in an iterative fashion. This prior (and, if specified, the interim prior of each iteration step) is returned. The final prior is used by ZEBRA to compute a posterior for each galaxy. The posterior can be saved as full 2D-table or in marginalized form. ZEBRA's output includes the most probable redshift and template type for each galaxy as defined by (i) the maximum of the posterior or (ii) after marginalizing over templates types and redshifts, respectively. The errors are calculated directly from the posterior.

ZEBRA can also be employed to derive template-based k-corrections using the specified templates and filters.

All input and output files of ZEBRA are ASCII-files.

1.2 The software license

This program is free software; you can redistribute it and/or modify it under the terms of the GNU General Public License (GPL) as published by the Free Software Foundation; either version 3 of the License, or (at your option) any later version.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License 3 for more details.

A copy of the GPL 3 is provided at the end of this manuscript.

1.3 Usage and questions

It is kindly requested that the use of ZEBRA should be acknowledged with an explicit reference to Feldmann et al. (2006) in the bibliographic list of any resulting publication.

Any problems, comments and suggestions should be sent via e-mail to zebra@phys.ethz.ch.

2 Getting started

2.1 About this package

The package contains the following subdirectories and files:

- **src**: The source code of ZEBRA v1.0. How to compile ZEBRA from source is described in 2.2.
- **doc**: This user manual.
- **scripts**: Bash-Shell scripts for ZEBRA demonstrating its different run modi. We suggest to start using ZEBRA with the help of these scripts and modify them accordingly. More information about the provided scripts can be found in 2.4.
- **examples**: These directories contain the needed input files and generated output files by the provided scripts.

2.2 Installing ZEBRA

This version provides ZEBRA pre-compiled in several binary formats and as source code. The binaries and the source code package can be downloaded from the ZEBRA website at

<http://www.exp-astro.phys.ethz.ch/ZEBRA>.

We now explain how to install ZEBRA from source code. First you should read the **README** file in the **src** directory. Then, before you can compile the ZEBRA package you have to make sure that the BLAS library (**blas**), the Lapack library (**lapack**), the GNU scientific library (**gsl**) and the Lapack++ library (**lapackpp**) are installed on your system.

The first two libraries are installed on most systems, but the GNU scientific library and the Lapack++ library may be missing on your system. If libraries are not installed on your system you can either install them locally, e.g. in your home directory¹, or you can ask your system administrator to install them in a directory accessible by all users.

After making sure that the aforementioned libraries are present, you may install ZEBRA as follows:

1. Type `./configure --prefix installation-path` in the top directory of this package. The directory *installation-path* is some directory for which you have write permissions, e.g. use the local directory `$PWD`. If you have installed **lapackpp** in some directory that is not automatically detected by the `configure` script you will have to call `configure` with additional options specifying the directory. Enter `configure --help` to obtain a list of all available installation options. The `configure` script sets conservative compiler optimizations according to your hardware. You can compile ZEBRA with your preferred compiler optimizations by running `configure` with the option `CFLAGS=your-compiler-optimization`.
2. Type `make` and `make install` to compile the source code and to copy the binary into *installation-path/bin*.

¹We suggest you install them into `$HOME/local`

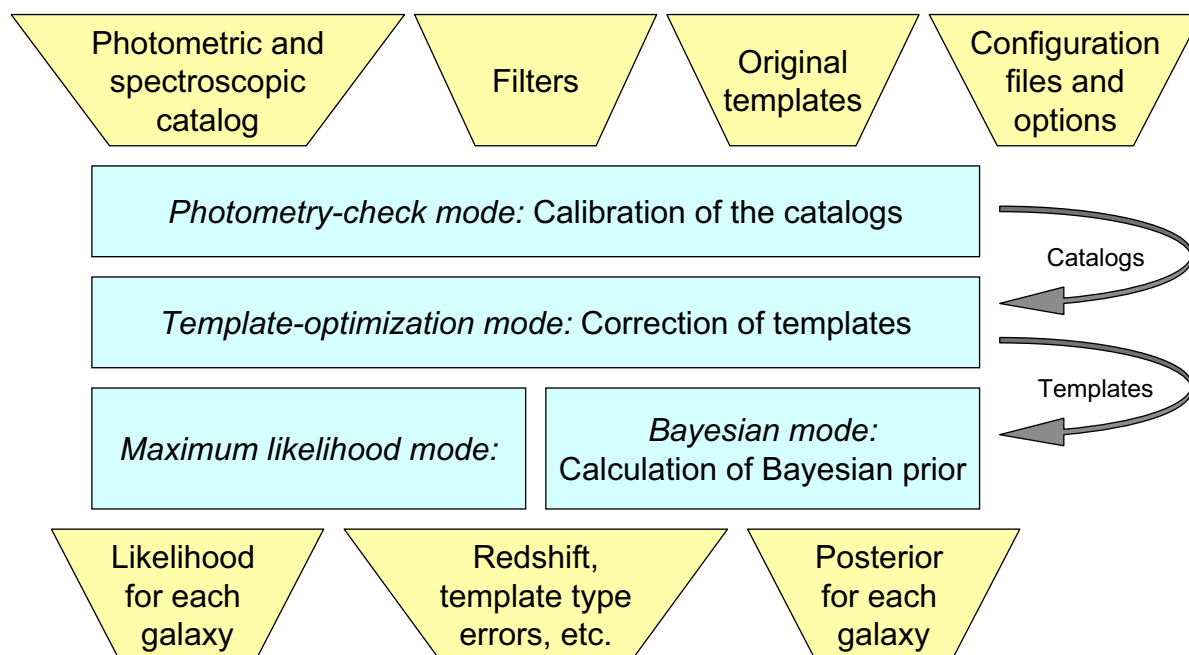


Figure 1: The design of ZEBRA. The different operation modi are explained in the text.

2.3 Checking the installation

If you want to test the binary of ZEBRA enter the `bin` directory and type `zebra -h`. If everything is fine, ZEBRA will print a complete list of its available options. Be aware that not all available options (especially those which are not described in this manual) are necessarily well tested.

2.4 How to use ZEBRA

ZEBRA is controlled via command-line options or (more conveniently) with the help of wrapper scripts. A complete list of all available options and their default values can be obtained by calling ZEBRA with the option `--help` or `-h`.

In this section we first demonstrate how ZEBRA is used in conjunction with command-line options. Later on we describe how to use ZEBRA conveniently with the provided wrapper scripts.

Fig 1 shows the various run modi of ZEBRA. Do not worry if you do not understand all of them at this point. The run modi are explained in detail in section 4.

Using ZEBRA from the command line: Let us have a look at the contents of the directory `examples/ML_notImproved`

```
>ls -l examples/ML_notImproved/
filter.conf
template.conf
testCatalog.cat
testCatalog.cat.def
```

The files `filter.conf` and `template.conf` specify which filters and templates are to be used by ZEBRA. The filter and template files are stored in `examples/filters/` and `examples/templates/`. The photometric catalog is denoted `testCatalog.cat` and has an associated definition file `testCatalog.cat.def`. The latter tells the program which columns of the catalog file correspond to which filters, which columns contain redshift information and also allows one to set minimum errors for photometric fluxes. The content of `testCatalog.cat.def` is shown in fig. 2.4.

Let us enter the directory `examples/ML_notImproved`

```
>cd examples/ML_notImproved
```

and call ZEBRA in Maximum-Likelihood mode:

```
>zebra -c testCatalog.cat -F ../filters -T ../templates -k -i 5
-z 0 -Z 2 -D 0.005
```

This example assumes that you have included the location of the ZEBRA binary in your `$PATH` variable. If not, you should call the executable of ZEBRA by its full filename (incl. the path).

Options are passed to ZEBRA by the common getopt/getoptlong-syntax. This means that you can specify options either with a dash followed by a single letter or a double-dash followed by a keyword. In our example the first three options denote the catalog file to read, the location of the filter transmission curves and the location of the templates. The option `-k` specifies that ZEBRA is run in Maximum-Likelihood mode. The number of log-interpolated templates is set to 5 with the command `-i 5`. The range (from 0 to 2) and width (0.005) of the redshift grid is set with the options `-z 0 -Z 2` and `-D 0.005`, respectively.

Upon successful termination of ZEBRA the file `ML.dat` is created in the current directory. This file summarizes all relevant information about the catalog entries, e.g. the best fit redshift and template type. A detailed header describes all contained columns.

Using ZEBRA with wrapper-scripts: Enter the `scripts` directory below the top-level directory of the package and open the Perl script `callzebra_ML_notImproved`. It sets various path variables, the name of the catalog containing the photometric data, various options and finally calls ZEBRA with all these options. Executing the script by entering `callzebra_ML_notImproved` will run ZEBRA and create the output file `ML.dat` in the directory `examples/ML_notImproved` as before.

Each of the provided scripts demonstrates one of the different run modi of ZEBRA. In particular:

- `callcatalogCorrect`: Runs ZEBRA in *photometry-check mode*.
- `callimprove`: Runs the *template-optimization mode* of ZEBRA. It creates improved templates.
- `callzebra_ML_notImproved`: Runs ZEBRA in *Maximum-Likelihood mode* on a catalog consisting of (only) 10 objects using default templates.
- `callzebra_M_improved`: Same as before but now (previously) improved templates are used. Please note, the “improved” templates used in this example are only toy templates and should not be used for scientific purposes.

# column_name		column_number	minimum_magnitude	error
#	type(F,dF,Z)	1-sigma	magnitude	
#				
z_cat	Z	17		
z_phot	Z	18		
u_cfht.res	F	1		
B.res	F	3		
g.res	F	5		
V.res	F	7		
r.res	F	9		
i.res	F	11		
z.res	F	13		
flamingos_Ks.res	F	15		
u_cfht.res	dF	2	x	0.05
B.res	dF	4	x	0.05
g.res	dF	6	x	0.05
V.res	dF	8	x	0.05
r.res	dF	10	x	0.05
i.res	dF	12	x	0.05
z.res	dF	14	x	0.05
flamingos_Ks.res	dF	16	x	0.2

Figure 2: The content (shortened) of the catalog definition file `testCatalog.cat.def`. The first column associates a name to each column of the catalog file. If this column contains flux or flux error information the given name is matched with the filter names from `filter.conf`. The second column in `testCatalog.cat.def` specifies the type of the column. Here F, dF and Z stand for filter band, filter band error and redshift information, respectively. An upper-limit magnitude is specified in the fourth column of the filter band error entries and a minimum magnitude error in the fifth column. Missing columns are marked with an x.

file name	filter description
u_cfht.res	CFHT U*
B.res	Subaru B
V.res	Subaru V
g.res	Subaru g+
r.res	Subaru r+
i.res	Subaru i+
z.res	Subaru z+
flamingos_Ks.res	KPNO/CTIO Ks

Table 1: The provided filter files in this release (and many more) are publicly available at <http://www.astro.caltech.edu/~capak/cosmos/filters>.

- `callzebra.Bayes`: Demonstrates how ZEBRA is run in *Bayesian mode*.
- `callkCorrect`: Runs ZEBRA in *k-Correction mode*.

Please note that all scripts can be executed independently from each other. **We do not claim that the values provided in the scripts are necessarily well suited for the provided examples nor for your specific application. We encourage you to test carefully which option values are appropriate for your application.**

3 Basic files and settings

This section describes both the syntax of many options and the layout of the basic files needed in almost every ZEBRA session. Please note that all input and output files of ZEBRA are ASCII files in a column-based, white-space separated table-format. Individual lines may be commented out by prepending a hash (#) sign.

3.1 Directories

All directories can be specified with ZEBRA's basic options (see 3.8). Each unspecified input or output directory defaults to the local directory.

3.2 The filter files

Filter files describe the transmission curve of a filter bands. The first column in each filter file specifies the wavelength in Å and the second column the photon transmittance (between zero and one). The wavelength values need to grow strictly monotonically from top to bottom of the filter file. ZEBRA checks whether this is fulfilled and prints a warning if not.

This package provides some filter files in the `examples/filters` directory, see Table 1.

ZEBRA needs the specification of one designated filter (we will call it B-filter throughout this manuscript)

- to ensure an absolute magnitude cut,
- to output absolute magnitudes,

file name	template description	source
El_cww.sed	elliptical galaxy	Coleman et al. (1980)
Sbc_cww.sed	Sbc galaxy	Coleman et al. (1980)
Scd_cww.sed	Scd galaxy	Coleman et al. (1980)
Im_cww.sed	irregular galaxy	Coleman et al. (1980)
SB3_kin.sed	starbursting galaxy	Kinney et al. (1996)
SB2_kin.sed	starbursting galaxy	Kinney et al. (1996)

Table 2: The provided template files in this release are publicly available as part of the BPZ package (<http://acs.pha.jhu.edu/~txitxo/bayesian>).

- to normalize the templates.

The designated filter band *does not need* to be one of the filter bands of the photometric catalog. The only requirement is that the filter file is also present in the filterpath.

The filename of the designated filter can be specified with the `--b-filter-name` option, the default is `B.res`.

3.3 The template files

Each template file contains the SED of a real or synthetic galaxy in the following format. The first column specifies the wavelength in Å and the second the spectral flux density (per unit wavelength and with arbitrary scale). The wavelength values need to grow strictly monotonically from top to bottom of the template file. ZEBRA checks whether this is fulfilled and prints a warning if not.

This package provides some template files in the `examples/templates` directory, see Table 2.

Depending on the redshift range of interest you will need to make sure that all your templates cover a sufficiently large wavelength range. Otherwise you will lose some filter bands. The reason is that ZEBRA selects the best fit based on the global minimum χ^2 and therefore it can only safely use the filter bands for which fluxes can be calculated for all redshifts and all templates. ZEBRA will warn you if your templates need to be extended to shorter wavelength (“UV”) or longer wavelength (“IR”).

3.4 The catalog file

This file contains the photometric data (and spectroscopic redshifts if available) of the galaxies in question. Each row corresponds to an individual galaxy. The rows contain the photometric magnitudes (must be given in AB magnitudes), corresponding magnitude errors, the redshift (if available) and possible other information, e.g. an ID. The latter information is currently ignored by ZEBRA.

The assignment of the given rows to their filter bands etc. is specified in the catalog definition file, see 3.5.

ZEBRA converts all magnitudes and magnitude errors into flux densities (in $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$) and *relative* flux density errors according to the following formulae:

$$\text{flux} = 10^{-0.4(\text{mag}+48.6)}, e(\text{flux}) = e(\text{mag}) \log(10.)/2.5$$

column	content type	content	remark
1	string	filter name	
2	integer	filter used (1) or not used (0)	optional, default: 1

Table 3: The structure of the filter configuration file. Each entry has to be written on a single line. Comment lines have to start with #.

A magnitude entry ≥ 99 in a filter band is recognized as too weak a signal to be detected. A magnitude entry ≤ -99 is recognized as not being measured.

If for a given galaxy no magnitude in a filter band is specified (-99) that filter band is discarded, i.e. not used in the Maximum-Likelihood redshift estimation of that galaxy. If the magnitude is non-detected (99) but a valid magnitude error is given, i.e $0 < \text{error} < 99$, the magnitude is either set to a provided “1- σ -magnitude” (see 3.5) or otherwise the filter band value is discarded for this galaxy. If the considered filter band contains a valid magnitude (> -99 and < 99) but the error is not valid, the error will be either set to the minimum magnitude error if (i) this error is provided in the catalog configuration file and (ii) the option `--allow-missing-error` is enabled, or the filter band is discarded otherwise. If a minimum magnitude error is provided, all magnitude errors in the catalog will be increased if necessary to be at least equal to this minimum magnitude error.

For the benefit of the user ZEBRA displays a warning (and this is all it does) if some magnitude in the catalog is out of a given range. This range (the default is from 5 to 35) can be specified with the `--mag-catalog-low` and `--mag-catalog-high` options.

The catalog name has to be supplied to ZEBRA with the `-c` option.

3.5 The standard configuration files

The configuration files determine (i) which templates and filters are used by ZEBRA and (ii) the structure of the catalog file.

In the following we assume for sake of simplicity that the default file names of the configuration files are used, i.e. `filter.conf`, `template.conf` and `catalog.def`. Here *catalog* is the name of the photometric catalog. The names can be changed with the options `-f filter-conf-file`, `-t template-conf-file` and `-d catalog-def-file` respectively.

The structure of the configuration files is shown in detail in tab. 3, tab. 4 and tab. 5 and will be explained below.

The first two configuration files specify which filters and templates are available to the program.

Each row of `template.conf`, excluding comments, corresponds to a template file. Each row may consist of several columns. The first column specifies the template name, which is obligatory; the other columns are optional. The second column may contain a 1 (in this case ZEBRA will use this template, which is the default) or a 0 (ZEBRA will ignore this template). The 3rd and 4th column are used to specify minimum and maximum ranges of the template. These columns should not be used in this release of ZEBRA but might be useful in future extensions. The 5th column can contain a mass-to-light ratio (default 1), which is used in the construction of the linear interpolated templates. The 6th column may contain the name of a file with ρ and σ values specifically for this template. This file is described in more detail in 3.6. In order to address a column without specifying the values of preceding columns the special value “x” may

column	content type	content	remark
1	string	template name	
2	integer	template used (1) or not used (0)	optional, default: 1
3	float	lower redshift limit	optional, default: 0
4	float	upper redshift limit	optional, default: 10
5	float	mass to light ratio in B-band	optional, default: 1
6	string	name of rho-sigma-file	optional, no default

Table 4: The structure of the template configuration file. Each entry has to be written on a single line. Comment lines have to start with `#`. The lower and upper redshift limits are used to restrict the use of templates to a certain redshift range (see options `--chi2-add` and `--chi2-mult`). However, the use of those options is not recommended. The mass-to-light ratio (default 1) is used in the construction of linear interpolated templates. The last column may state the name of a file containing σ^2 and ρ^2 values which are used in the *template-improvement mode*, see 3.6.

column	content type	content	remark
1	string	column name	the filter name or (arbitrary) name for a redshift column
2	string	column type	one of F, dF, Z, dZ
3	integer	column number	starting with 1
4	float	1- σ magnitude	optional; only for dF; no default
5	float	minimum magnitude error	optional; only for dF; no default

Table 5: The structure of the catalog configuration file. Each entry has to be written onto a single line. Comment lines have to start with `#`.

be used.

The layout of `filter.conf` is similar. For each row up to two columns are recognized by ZEBRA. The first column contains the full filter name (e.g. `B.res`), the second column is optional and may contain a 1 (i.e. ZEBRA will use this filter, which is the default) or 0 (i.e. ZEBRA will ignore this filter). Since the columns of the photometric catalog are defined in the `catalog.def` file it might happen that not all filters in `catalog.def` are mentioned in `filter.conf` or not all filters in `filter.conf` are actually used in `catalog.def`. In these cases ZEBRA will only consider the filters which are mentioned in both files.

The catalog definition file specifies which columns of the catalog file contain the magnitudes and errors of which filter band. Each row consists of at least 3 columns. Additional columns carry facultative information. The first column contains the full filter name if this particular row specifies a filter band or a filter band error. Otherwise it might contain an arbitrary string. The third column denotes the column number in the catalog file to which this row corresponds. The second column contains one of the following labels: `F`, `dF`, `Z`. According to the provided label ZEBRA decides whether the respective column in the catalog file corresponds to the magnitude in a filter band, the magnitude error in a filter band or a redshift column. The available options described by the facultative columns depend on the label. In filter bands rows (`F`) a 4th column is recognized by ZEBRA as specifying a zero-point offset. In filter band errors rows (`dF`) the 4th column may contain a “1- σ magnitude” and the 5th column a minimum magnitude error. Again, the special value “x” may be used to address a column without specifying the values of preceding columns.

The zero-point offset is subtracted from the corresponding filter band magnitude when the catalog is read by ZEBRA. Please do not rely on this special feature but run ZEBRA in *photometry-check mode* (see 4.1) to accurately remove offsets from the catalog itself. The 1- σ magnitude is used as an upper magnitude limit for galaxy entries with “non-detected” magnitudes in the catalog file (see 3.4). The minimum magnitude error offers the user the possibility to enforce a lower limit on the *relative* flux errors seen by ZEBRA. This is sometimes necessary because a small flux error in a filter band can strongly influence the outcome of Maximum-Likelihood method. Please note that the photometric errors provided in the catalog usually do not include, e.g., errors due to missing or mismatching templates. Using sensible errors, however, is very important in order to obtain robust photometric redshifts.

3.6 Other configuration files

We now briefly describe files which are specific to certain run modi of ZEBRA. More information can be found in the section discussing the corresponding run mode.

The catalog-correction configuration file (default `catalogCorrection.def`) is an input file used in the *photometry-check mode*. It gives an account of the filter bands to be corrected and how the correction is done (number of magnitude bins, regression type, limits of correction, ...).

The template-improvement configuration file (default `templateImprovement.def`) is an input file used in the *template-improvement mode*. It specifies the limits of the redshift bins employed in the template improvement.

3.7 Basic output files

In *photometry-check mode*, *template-optimization mode* or *Maximum-Likelihood mode* ZEBRA produces a file with (default) name `ML.dat`. In the *Bayesian mode* a very similar file with the

(default) name `Bayes_ML.dat` is created.

`ML.dat` contains in tabulated form the results of the Maximum-Likelihood fit applied to the catalog entries, while `Bayes_ML.dat` contains in a similar fashion the outcome of the Bayesian (maximum posterior) analysis. Likelihood or posterior functions for individual catalog entries can be obtained by enabling the appropriate `--likelihood` or `--posterior` option.

The prefix (ML) of the file `ML.dat` can be changed with the option `--outputbase filename`. When **ZEBRA** is run in *Maximum-Likelihood mode* the file contains the following information:

- Each no-comment line corresponds to the same no-comment line from the catalog file, i.e. the results are printed in the order of the input catalog.
- The spectroscopic redshift and the number of filter bands used in the fit.
- The set of estimated redshift z , template type t , normalization (quantity a defined in eq. A1 of Feldmann et al. (2006)), χ^2 , absolute magnitude (in the designated filter band, see 3.2), luminosity distance for following cases: (i) the pair (z, t) corresponding to the maximum of the likelihood $L(z, t)$ (i.e. the minimum of $\chi^2(z, t)$), (ii) the pair (z, t) corresponding to the maximum of the marginalized likelihood $L(z)$ and the template which is best fit with that redshift, (iii) the pair (z, t) corresponding to the maximum of the marginalized likelihood $L(t)$ and the redshift which best fits this template type.
- Errors for the redshift and template type estimates using (i) constant χ^2 boundaries (ii) percentiles of the marginalized likelihood functions.

An estimated redshift z of -1 indicates that **ZEBRA** was not able to perform the χ^2 fit. This might happen if, e.g. not enough filter bands were available or the absolute magnitude cut discarded the catalog entry (option `--mb-mode 1`).

If the `--normalize-templates` option is specified, **ZEBRA** normalizes all provided templates to unity flux-density per unit wavelength in the dedicated B-filter. However, the use of this option is only necessary if you want to use linearly interpolated templates. The conversion factor between original and normalized template is displayed if you run **ZEBRA** with verbosity 2 or higher. You will need to multiply the normalization given in `ML.dat` with this conversion factor to obtain the total normalization w.r.t. the original template.

We will now explain how the template number that **ZEBRA** outputs relates to the input templates provided to **ZEBRA**. Let n be the total number of template names (first column) in the template configuration file that are active, i.e. the corresponding second column is 1 or is not given (in which case the value defaults 1). We call these templates “basic templates” in order to distinguish them from interpolated templates created internally within **ZEBRA**. If no interpolated templates are used the template number t which **ZEBRA** outputs corresponds to the $t + 1$ -th active template in the template configuration file. Let us now assume that **ZEBRA** is run with $l \geq 0$ logarithmically interpolated templates. The template types range now from 0 to $(n - 1)l + n - 1$. This range corresponds to a smooth sequence of basic and interpolated templates with 0 corresponding to the first basic template and $(n - 1)(l + 1)$ to the last. If type t is a multiple of $l + 1$ it corresponds to the $t/(l + 1) + 1$ -th basic template in the template configuration file. Otherwise t describes a log-interpolated template between the $\lfloor t/(l + 1) \rfloor + 1$ -th and the $\lceil t/(l + 1) \rceil + 1$ -th basic template, where $\lfloor x \rfloor$ denotes the largest integer not exceeding x and $\lceil x \rceil$ the smallest integer not smaller than x . For example, consider the case that 6 basic templates and 5 log-interpolations between each pair of adjacent basic templates are used. Then

the template types range from 0 to 30, the template numbers 0, 6, 12, 18, 24 and 30 denote the 6 basic templates and all other template numbers denote interpolated templates.

The infix (ML) of the file `Bayes_ML.dat` can be changed with the option `--outputbase filename`. This output file contains the following information.

- The spectroscopic redshift and the number of filter bands used in the fit.
- The set of estimated redshift z , template type t , normalization (quantity a defined in eq. A1 of Feldmann et al. (2006)), χ^2 , absolute magnitude (in the designated filter band, see 3.2), luminosity distance for following cases: (i) the pair (z, t) corresponding to the maximum of the posterior $P(z, t)$, (ii) the pair (z, t) corresponding to the maximum of the marginalized posterior $P(z)$ and the template which is best fit with that redshift, (iii) the pair (z, t) corresponding to the maximum of the marginalized posterior $P(t)$ and the redshift which best fits this template type.
- Errors for the redshift and template type estimates using percentiles of the marginalized (i.e. summing over a parameter) and projected (i.e. fixing a parameter) posteriors.

More information about the entries in both output files can be found in the file header.

3.8 Basic options

The following options are very useful in almost all run modi:

- `--filterconf filename`: Filter-configuration file.
- `--filterpath pathname`: Directory containing the defined filters.
- `--templateconf filename`: Template-configuration file.
- `--templatepath pathname`: Directory containing defined templates.
- `--catalog filename`: Filename of the catalog file.
- `--catalogpath pathname`: Directory containing catalog file.
- `--catalogdef filename`: Filename of the catalog-configuration file.
- `--outputbase filename`: Basename (prefix) of the output file.
- `--outputpath pathname`: Directory to which output is written.
- `--zmin float`: Lower limit of allowed redshift range.
- `--zmax float`: Upper limit of allowed redshift range.
- `--dz float`: Difference between lowest redshift grid points.
- `--log-zBin`: Use redshift grid in $\log(1+z)$ instead of binning linear in redshift.
- `--ig-absorption integer`: No intergalactic absorption (0), absorption according to Madau (1995) (1), or according to Meiksin (2006) (> 1), see 5.3.

- `--mb-mode integer`: This option specifies how to deal with entries for which the best fitting (redshift, template) pair implies an absolute magnitude out of range (in the designated filter band, see 3.2). (0) The fit result is used, (1) The fit result is discarded and the catalog entry is marked as non-fittable, (2) The fit result is discarded and the best fitting (redshift,template) pair which obeys the absolute magnitude is used as fit result.
- `--mb-low float`: Lower (brighter) limit of allowed absolute magnitude.
- `--mb-high float`: Upper (fainter) limit of allowed absolute magnitude.
- `--rightz`: Use spectroscopic redshift (if available).
- `--log-interpolation integer`: Number of interpolations in magnitude space (logarithmic interpolations) between each adjacent template pair.
- `--save-flux`: The calculated flux densities (per unit frequency) are saved into flux file (-x). The stored quantity is defined in eq. A3 of Feldmann et al. (2006).
- `--load-flux`: Flux densities (per unit frequency) are read from flux file (-x). The stored quantity is defined in eq. A3 of Feldmann et al. (2006).
- `--verbose integer`: Determines the level of verbosity of the program (default 1).
- `--help`: Prints information about all available options of ZEBRA.

Many of the aforementioned options have a single character abbreviation. Please call **zebra -h** to see the complete list of options available.

4 The different run modi of ZEBRA

ZEBRA can be run in various operation modi which are specified with the run-mode options in table 6.

In principle it is possible to start ZEBRA with multiple run-mode options activated (except for *template-improvement mode*). In this case ZEBRA executes the different modi sequentially in the following order *k-correction mode*, *photometry-check mode*, *Maximum-Likelihood mode*, *Bayesian mode*. The use of multiple run-mode options is not recommended.

A typical usage of ZEBRA is indicated in the work-flow diagram fig. 1. The first step is to calibrate the photometry, i.e. running ZEBRA in *photometry-check mode*. Subsequently the given templates may be improved. The template improvement reduces systematic under/overpredictions and the mean error of the redshift estimates. It is strongly recommended to use a training sample with *spectroscopic* redshifts in this mode (option `--rightz` has to be enabled). With a calibrated catalog and appropriate templates at hand ZEBRA can be run in *Maximum-Likelihood mode* and/or *Bayesian mode* on the photometric catalog to return final estimates for redshift, template type and other parameters.

The *k-correction mode* is an unrelated operation mode which allows to calculate k-corrections from the given templates. No photometric catalog is needed in this case.

run mode	what it does	command line option(s)
<i>photometry-check mode</i>	calibrates the photometry of a given photometric catalog	<code>--calc-catalog-correction</code> <code>--apply-catalog-correction</code> <code>--iterations-catalog-correction</code>
<i>template-optimization mode</i>	optimizes the given templates using a training sample of galaxies with known redshifts	<code>--improve-template</code>
<i>Maximum-Likelihood mode</i>	performs a Maximum-Likelihood fit for each galaxy in the catalog using the given templates.	<code>--calcLikelihood (or -k)</code>
<i>Bayesian mode</i>	estimates a prior from the catalog which is used to calculate the posterior for each galaxy.	<code>--calcBayesian (or -b)</code>
<i>k-correction mode</i>	derives template-based k-corrections using the specified templates and filters.	<code>--kcorrection</code>

Table 6: The different run modi of ZEBRA.

4.1 Running the photometry-check mode

This mode calibrates the photometry of a given catalog. Please refer to Feldmann et al. (2006) for more details.

Input:

- catalog file (section 3.4);
- filter and template files (section 3.2, 3.3);
- standard configuration files (section 3.5);
- **configuration file of catalog correction**, see below

Options and Explanations: The photometry correction consists of two steps. The first step is the regression.

1. For each filter band n in question the flux residual Δn between observed f_n and template-based flux f_n^T is calculated for each catalog entry.
2. The magnitude range of n is divided into different magnitude bins n_i and a constant or linear regression is performed on the data set n_i , Δn_i .

The second step is the application of the corrections to the filter bands of a catalog. Let f_n be the flux of a catalog entry in filter band n and $\Delta n(f_n)$ be the result of the regression, then $f_n \rightarrow f_n - \Delta n(f_n)$.

The following options are relevant

- `--calc-catalog-correction`: This enables the regression step and calculates and outputs the corrections of a given catalog.
- `--apply-catalog-correction`: If this option is enabled previously derived corrections are applied to a (possibly different) catalog. The output catalog has the ending `.corr`.
- `--iterations-catalog-correction integer`: The calculation **and** application of the catalog calibration is done in a single step and iteratively *integer* times. All intermediate corrections and calibrated catalogs are written out.
- `--catalog-correction-def filename`: Defines the name of the photometry-correction configuration file which contains, e.g. binning information for each filter band, see below. Default is `catalogCorrection.def`.
- `--catalog-correction-base filename`: Defines the basename (prefix) of the file into which catalog correction data is printed. Default is `catalogCorrection`.
- `--single-fit`: If enabled, each catalog entry is fitted by all provided filter bands and the flux residual in each filter band is then calculated as the difference between measured flux and best fit flux. If this option is disabled the flux residual in the filter band n is obtained from a χ^2 fit in which the error in band n is multiplied by a certain factor (given by `--downgrading-factor`), thereby reducing the influence of the band n to the fit. In principle this leads to a faster convergence of the photometry correction scheme. A downgrading factor of unity reduces this case to the correction mode with `--single-fit` enabled.
- `--downgrading-factor float`: The role of this factor is explained in the `--single-fit` option.

The configuration file `catalogCorrection.def` determines

1. which filter band will be corrected;
2. how many bins in magnitude space are used and what are their limits; and
3. which regression type is applied (constant offset or linear correction).

The structure of the file is shown in Table 7. The first column determines the full filter name subject to photometry correction. The next column contains the number of magnitude bins. This number should not be too large because otherwise some bins might not contain enough catalog entries. The third and fourth columns specify the lower (bright) and upper (faint) magnitude limits which are used to exclude very bright or faint galaxies from the regression. The 5th column denotes the applied regression mode. We recommend using a regression with a constant offset as first choice. The extrapolation mode determines how **ZEBRA** corrects objects with magnitudes out of the magnitude range specified in columns 3 and 4. The range of extrapolation is specified in the next two columns. Objects with magnitudes out of this range are subject to the same

column	content type	content	remark
1	string	filter name	
2	integer	number of magnitude bins	
3	float	lower magnitude bound	the actual bins are calculated from columns 2,3 and 4
4	float	upper magnitude bound	
5	integer	interpolation mode	constant regression (0) linear regression (1) regression of order n (n)
6	integer	extrapolation mode	analogous to interpolation mode
7	float	lower limit of extrapolation	optional, default: smallest magnitude found
8	float	upper limit of extrapolation	optional, default: largest magnitude found
9	float	resolution of magnitude binning	optional, default: 0.05
10	float	percentile rejection limit	optional, default: 0.954 reject all (0) reject none (1) use median, not mean (< 0)
11	integer	min. number of galaxies per mag. bin	optional, default: 10

Table 7: The structure of the catalog-correction configuration file where columns 1-5 are the most important columns. Each line corresponds to a different filter band. Comment lines have to start with `#`. Only for filter bands which are mentioned here a photometry correction is performed. As interpolation mode we recommend constant (0) or linear regression (1).

correction as objects with the nearest magnitude still within the extrapolation range. In this way discontinuities at the extrapolation limits are avoided. You should make sure that the extrapolation range is large enough if you employ non-constant corrections. The regression curve is sampled with the resolution given in column 9. In column 10 the user may specify that only a certain fraction l_Y of objects in each magnitude bin is used. The fraction $1 - l_Y$ of objects with the largest standard deviation from the mean flux-residual in that bin is rejected. Column 11 sets the minimum number of entries per magnitude bin. Bins with fewer objects are not considered in the regression. The last three columns are optional.

In the *photometry-check mode* either spectroscopic or photometric redshifts can be employed. The use of the former is recommended if they are available for a sufficient large subsample of the given photometric catalog. In this case the option `--rightz` has to be enabled. In its iterative mode ZEBRA calculates the necessary corrections and applies them to the given catalog. The `--apply-catalog-correction` option provides a convenient way of applying the calculated corrections to any other catalog.

Output: ZEBRA creates the following files in the *photometry-check mode*:

- **ML.dat:** This file summarizes the Maximum-Likelihood fit results **before** the photometry correction. If an iterative photometry correction is performed **ML.1.dat** corresponds to

the Maximum-Likelihood fit on the original catalog, while `ML.dat` corresponds to the Maximum-Likelihood fit run on the last-before-final corrected catalog. Hence, to obtain the Maximum-Likelihood results on the photometry-corrected catalog you need to run ZEBRA in *Maximum-Likelihood mode* on the final photometry-corrected catalog.

- `residual.dat`: The observed magnitude and the magnitude constructed from the best fit template is stored in this file.
- `catalogCorrection_filtername.corr`: Stores the regression curve (and the estimated errors) within the extrapolation limits, i.e. it contains the magnitude corrections as a function of magnitude.
- `catalogCorrection_filtername.stat`: Contains the residuals and their errors between observed and template-based magnitude for each magnitude bin. It also stores the regression results.
- `catalog.corr`: This is the calibrated catalog.

Files from intermediate iterations (not the final iteration) are distinguished by an additional `_1` suffix to the catalog correction base for the first iteration, `_2` for the second and so on.

The corrected catalogs (from `catalog_1.corr` until finally `catalog.corr`) store the corrections in a cumulative way. This is **not** true for the correction (`catalogCorrection_*`) files. Hence, the first iteration (i.e. the correction files with `_1`) usually gives the largest contribution to the total photometry correction.

The format and content of the catalogs that ZEBRA outputs depend on the options `--preserve-errors-output` and `--preserve-catalog-format`. When ZEBRA is run in the *photometry-correction mode* we recommend enabling these options.

Remarks:

- You should make sure that there is no systematic problem with your templates. You can combine the information in `ML.dat` and `residual.dat` to check that your corrections hold independently of template type. If you have problems with your templates you might want to skip the photometry correction step and proceed with the template improvement. However, without sensible photometry it is not clear whether template improvement will give you a trustworthy result. Alternatively you can still run the photometry correction mode and apply those corrections in all further steps while keeping in mind that in this case the corrections are internal to ZEBRA and do not have any physical meaning.
- We find empirically that trying to correct for more filter bands than actually necessary deteriorates the quality of the estimated photometric corrections. Hence, to obtain optimal catalog corrections one should try to correct as few bands as possible.
- Constant offsets should be the first choice for photometric corrections.
- If there are only very few spectroscopic redshifts available it might be worthwhile to run the photometry correction mode on a large catalog using the internally derived photometric redshifts instead (disable `--rightz` option).

4.2 Running the template-optimization mode

This mode creates optimized templates which increase the quality of redshift and template type estimates.

Input:

- catalog file (section 3.4);
- filter and template files (section 3.2, 3.3);
- standard configuration files (section 3.5);
- **configuration file for template optimization**, as described below;
- possibly a file specifying ρ^2 and σ^2 values for individual wavelength (see below);
- possibly such a file for each template (see below)

Options and Explanations: The following options are relevant:

- `--improve-template`: Activates the *template-optimization mode*. This mode cannot be combined with other run modi of ZEBRA.
- `--template-improvement-def filename`: Determines the file containing the redshift bins for the template correction. Default is `templateImprovement.def`
- `--correction-steps`: Number of iterations of the template improvement scheme.
- `--template-improvement-mode`: Uses the original templates as starting point of each iteration (0 - default) or takes the corrected templates (1). In the latter case the result depends on the iteration number and finally converges to the result for $\sigma \rightarrow \infty$.
- `--sigma float`: The smaller σ the higher the penalty for large deviations of the corrected templates from the old templates.
- `--rho float`: The smaller ρ the stronger is the regularization of the shape of the corrected templates (i.e. large gradients are increasingly suppressed as ρ becomes smaller).
- `--load-rho-sigma`: Indicates to use different ρ and σ values depending on wavelength and template type. The user can provide a global file with `--rho-sigma-load-base` or individual files for each template (see the description of the template configuration file in section 3.5). This option is not activated by default.
- `--save-rho-sigma`: Save a file containing ρ^2 and σ^2 values depending on wavelength. The output filename can be specified with the `--rho-sigma-save-base` option. This option is not activated by default.
- `--punish-gradient`: If this option is not activated, ρ is set to infinity, independently of the choice of the option `--rho`.

- `--rescale-with-mesh`: σ and ρ are rescaled with the square root and inverse square root of the grid spacing to remove dependencies on the mesh-spacing.
- `--rescale-with-flux integer`: σ and ρ are rescaled with the template flux to avoid over-corrections in the low-flux regions. Three different modi are available. (0) no rescaling, (1) σ and ρ scale with the square root of the flux, (2) σ and ρ scale proportionally with the flux. We recommend option (1).
- `--rescale-with-bands`: This option can be used to reduce the influence of the number of filter bands on the outcome of the template improvement. However, depending on this option, different ρ and σ values are required.

The configuration file `templateImprovement.def` defines the limits of the redshift bins for the correction. Each redshift bin is handled by ZEBRA in an independent manner. The file contains only one column and needs to consist of at least two rows. The row values have to increase monotonically from top row to bottom row. The first row determines the low-redshift limit of the first redshift bin, the second row specifies the high-redshift limit of the first redshift bin and simultaneously the low-redshift limit of the second bin etc.

In addition to global ρ and σ values which hold for all templates and wavelengths the user may specify (using the option `--load-rho-sigma`)

- a file containing σ^2 and ρ^2 values for individual wavelengths (default `rhoSigma.dat`),
- such a file specific for each template.

Each of those files needs to consist of at least two columns containing σ^2 and ρ^2 , respectively. The number of rows has to be identical to the size of the wavelength mesh used in the template optimization. The easiest way to create such a file is to first to run ZEBRA with the option `--save-rho-sigma` (and `--load-rho-sigma` disabled) and then to copy/modify the resulting output file.

Output: The following files are written when ZEBRA is run in *template-optimization mode*:

- `Template_corr_itI1T.dat`: Contains the spectral energy distribution of template number T after $I+1$ iteration steps. All templates, i.e. the original templates, the corrected templates and all interpolations are included in this enumeration.
- `template-filename_corr_itI_zgtzlow_zltzhigh.dat`: Contains the spectral energy distribution of the corrected basic template with original name *template-filename* after $I+1$ iterations which has been optimized for the redshift range *zlow-zhigh*.

The option `--rightz` is **not** automatically activated when this operation mode is used.

Remarks:

- The optimal choice of σ and ρ depends on the data at hand. In any case you should look at the improved templates and judge whether their shapes are sensible or not. Extreme wiggles may indicate that ρ is too high, while too strong changes of the templates can originate from a too high σ . In addition, having too few catalog entries (for a given redshift bin and given type) can imply non-physical template shapes due to over-fitting.

- You should check that your redshift binning scheme does not lead to artificial peaks and voids in the redshift distribution near the bin boundaries. In order to minimize such spurious effects we recommend running the *template-optimization mode* twice, with interlaced redshift binning schemes, and then to combine the optimized templates.

4.3 Running the Maximum-Likelihood mode

This mode estimates redshift, template type and other parameters using a Maximum-Likelihood approach.

Input:

- catalog file (section 3.4);
- filter and template files (section 3.2, 3.3);
- standard configuration files (section 3.5);

Options and Explanations: The following options are relevant:

- `--calcLikelihood` or `-k`: Runs ZEBRA in *Maximum-Likelihood mode*.
- `--likelihood full`: Saves the 2D (redshift and template type) likelihood function $L(z, t)$ for each galaxy
- `--likelihood t`: Saves the marginalized likelihood function $L(t)$.
- `--likelihood z`: Saves the marginalized likelihood function $L(z)$.
- `--likelihood pz`: Saves the marginalized likelihood function $L(z)$ in form of percentiles.
- `--dump besttemplate`: Saves for each galaxy the best fit template. The template is normalized to best fit the observational data.
- `--dump templates`: Saves for each galaxy all fitted templates (for diagnostics). The templates are normalized to best fit the observational data.
- `--dump fluxes`: Saves the fluxes in each filter band of each galaxy.
- `--dump residual`: Saves the observed and template-based flux in magnitudes in each filter band for each galaxy.
- `--single`: If activated all the output specified with `--likelihood` and `--dump` is printed into a single file. Otherwise individual files are generated for each galaxy.

Output: The results of the *Maximum-Likelihood mode* are stored in the file `ML.dat`. This file is described in detail in section 3.7. Additional output files can be specified with the `--likelihood` or `--dump` option. Their layout is explained by a header within each file.

4.4 Running the Bayesian mode

This mode estimates redshift, template type and other parameters using a Bayesian approach. The prior is calculated in a self-consistent way from the given photometric catalog.

Input:

- catalog file (section 3.4);
- filter and template files (section 3.2, 3.3);
- standard configuration files (section 3.5);

Options and Explanations: The following options are relevant:

- `--calcBayesian` or `-k`: Runs ZEBRA in *Bayesian mode*.
- `--calc-prior`: The prior is calculated iteratively (starting with a flat or loaded prior).
- `--calc-prior-mode integer`: Calculate prior in redshift and template space (0) or taking projected prior using the best fit template (1).
- `--max-iterations integer`: The number of prior calculation steps.
- `--smoothprior`: Prior is smoothed after each iteration. The size of the smoothing kernel is set with `--smootht` and `--smoothz`.
- `--smootht float`: FWHM of rectangular smoothing kernel per template in template space. *float* has to be non-positive if no smoothing is wanted.
- `--smoothz float`: FWHM of rectangular smoothing kernel in red shift space. *float* has to be non-positive if no smoothing is wanted.
- `--smoothz-mode integer`: Smoothing mode for prior in redshift space. Possible choices are a fixed kernel width (0) or an adaptive width (1), i.e. scaling with $(1 + z)$.
- `--load-prior`: Prior is read from file (specified with `--prior-load-base`).
- `--save-prior`: Calculated prior saved into file (specified with `--priorbase`).
- `--save-prior-iterative`: Prior is saved after each iterative step.
- `--priorbase filename`: Basename (prefix) of file storing the prior $P(z, t)$.
- `--prior-load-base filename`: Basename (prefix) of file containing the prior to load.
- `--priorpath pathname`: Directory containing the prior file.
- `--posterior full`: Saves the 2D-posterior $P(z, t)$ for each galaxy.
- `--posterior t`: Saves the posterior $P(t)$ marginalized over redshifts.
- `--posterior z`: Saves the posterior $P(z)$ marginalized over template types.

- `--posterior pz`: Saves the posterior $P(z)$ marginalized over template types as percentiles.
- `--single`: If activated, all the output specified with `--posterior` is printed into a single file. Otherwise individual files are generated for each galaxy.

Output: The results of the *Bayesian mode* are stored in the file `Bayes_ML.dat`. This file is described in detail in 3.7. Additional output files can be specified with the `--posterior` option. Their layout is explained by a header within each file.

4.5 Running the k-correction mode

In this run mode ZEBRA returns k-corrections based on the given templates and filter bands.

Input:

- filter and template files (section 3.2, 3.3);
- filter and template configuration files (section 3.5);

Options: The *k-correction mode* is chosen by the option `--kcorrection`.

Output: The following output files are created.

- `kCorrection.dat`: Contains magnitudes for each template in each filter band as a function of redshift. The flux is not normalized as only flux ratios, i.e. magnitude differences, are of interest.
- `kCorrection_real.dat`: Contains for each template the k-Correction (as a function of redshift) according to the definition of Hogg et al. (2002). The used formula is also stated in the header of this file. The first filter in the filter configuration file defines the rest-frame band, the second filter the observed-frame filter band.
- `kCorrection_zero.dat`: Contains the so-called color-k-correction for each template as a function of redshift. The applied formula is stated in the header of this file. The first filter in the filter configuration file defines the rest-frame filter band, the second filter the observed-frame filter band.

5 Background Information

5.1 Extensions of templates and the mesh

ZEBRA complains if a template is too short on either the short- or long-wavelength side as described in 3.3. The user has then either to enlarge the template appropriately or to reduce the redshift range in question. An additional complication arises if ZEBRA is run in *template-improvement mode* or if the user enables the `--use-mesh` option. In this case each template and filter is re-sampled on a mesh. If the mesh contains less wavelength sampling points than the original templates ZEBRA will run faster. The user should ensure, however, to use a high enough resolution (this depends also in the filters used). The properties of the mesh can be set with

the options `mesh-lambda-min`, `mesh-lambda-max` and `mesh-lambda-res`. The mesh has to be included in the original template range, otherwise ZEBRA will output a warning. In conclusion, the wavelength range of the mesh has to be included in the wavelength range of all templates, but it has to be large enough that fluxes in all filter bands at all considered redshifts can be calculated.

5.2 The use of cosmological parameters

The cosmological parameters Ω_M , Ω_Λ and h in 100 km/s/Mpc are (only) used to transform apparent magnitudes into absolute magnitudes, e.g. to ensure the absolute magnitude cut. The user may change the default values with the `--omegaM`, `--omegaL` and `--hubble` options. Calling ZEBRA with higher verbosity (`-v 3`) will print (among other information) a table containing the luminosity distance D_L on the screen. The cosmology does not need to be a flat one, i.e. ZEBRA assumes $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$.

5.3 The intergalactic absorption

ZEBRA can take the attenuation of templates at high redshifts due to intervening intergalactic hydrogen into account. The attenuation is mainly caused by resonant scattering of Lyman-series transitions (LT) and by photoelectric absorption due to optically thin (OT) or Lyman-limit (LL) systems. The parameter `ig-absorption` controls the employed attenuation recipe: (0) no attenuation is used, (1) attenuation (LT+OT+LL) according to Madau (1995) (considering L_α - L_δ transitions), (2) LT absorption according to Meiksin (2006) (considering the first 40 line transitions) and OT+LL according to Madau (1995), (3) attenuation (LT+OT+LL) according to Meiksin (2006), (4) attenuation (LT+OT+LL) according to Meiksin (2007), (5) attenuation (LT+OT) according to Meiksin (2007), (6) only LT attenuation according to Meiksin (2006). The different attenuation recipes implemented in ZEBRA are shown in Fig 3 and should be compared with Fig 3 of Madau (1995) and Fig 1 of Meiksin (2006).

5.4 Flux densities and normalization

ZEBRA operates internally on flux densities (per unit frequency). Catalog entries are given in magnitudes and are converted to flux densities as described in 3.4. The flux density (per unit frequency) in a certain filter band of a red-shifted template is calculated according to eq. A3 of Feldmann et al. (2006). This is done *before* any Maximum-Likelihood fit is performed and thus independent of the actual values of the provided catalog. The flux-densities can be saved and/or loaded with the `--save-flux` and `--load-flux` options in order to save time in case ZEBRA is run multiple times with the same set of templates, filters and redshift binning.

You can use the saved fluxes to calculate the template-based magnitudes for each galaxy in each filter (although there are also other ways to do this, see 4.3, in particular options `--dump residual` and `--dump fluxes`). You need to extract the flux corresponding to the best-fit template and the best-fit redshift of the desired filter band from the saved flux-file and multiply it with the best-fit normalization. Then you convert this flux density into a magnitude according to 3.4. Best-fit redshift (column 3), best-fit template (column 4) and best-fit normalization (column 5) can be found in `ML.dat`. If you want to convert a flux density per unit frequency f_ν into a flux density per unit wavelength f_λ you need to divide f_ν by the square of the pivot-wavelength of

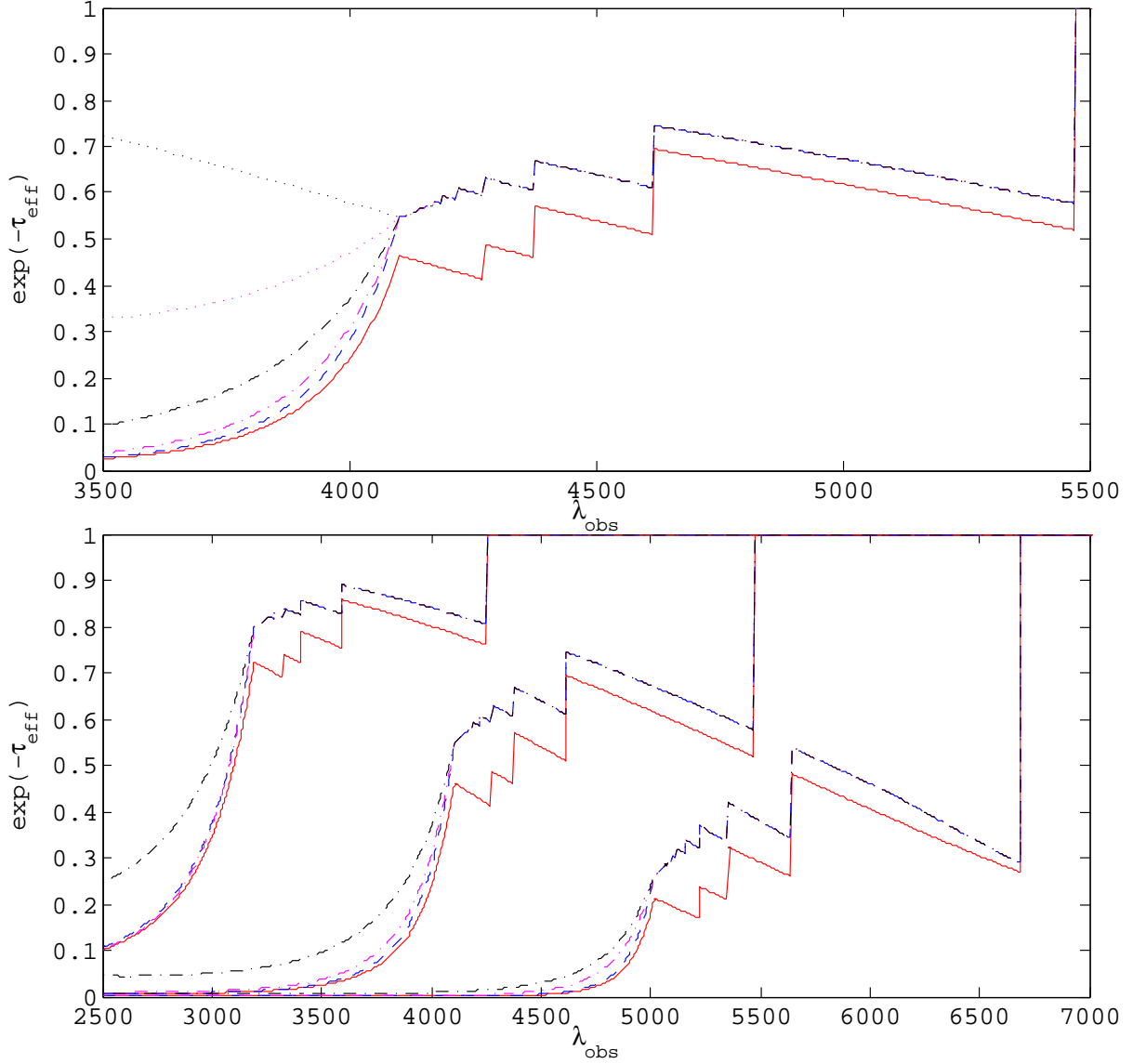


Figure 3: Mean intergalactic transmission vs observed wavelength. (Top) For an object at redshift 3.5 and for different attenuation recipes enumerated by the value of the `ig-absorption` parameter (see text): 1 (red solid line), 2 (blue dashed line), 3 (magenta dot-dashed line), 4 (black dot-dashed line), 5 (magenta dotted line), 6 (black dotted line). (Bottom) As in the top panel, but for objects at redshift 2.5 (left), 3.5 (middle), 4.5 (right).

each filter. The pivot-wavelengths of the filters are printed (among other information) if **ZEBRA** is run with `--verbose 2`.

ZEBRA offers the possibility of normalizing input templates to the dedicated B-filter using the `--normalize-templates` option. Its application can change the values in the flux file and the best-fit normalization but not the best-fit template or the best-fit redshift unless linearly interpolated templates are used. If only logarithmically interpolated templates are employed the normalization of the template files has no influence on the result of a Maximum-Likelihood or Bayesian run.

6 Experimental features

Several features are implemented in the current version of **ZEBRA** which are not explained in this manual. They are neither necessarily well tested nor fully functional and you should avoid using them. They are:

- `--chi2-add`
- `--chi2-mult`
- `--lin-interpolation`
- `--improve-template-mode 1`
- `--smoothz-mode 2`

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Version 3, 29 June 2007

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